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A Case Study Of Cumulus Formation Beneath A Stratocumulus Sheet: Its Structure And Effect On Boundary Layer Budgets.

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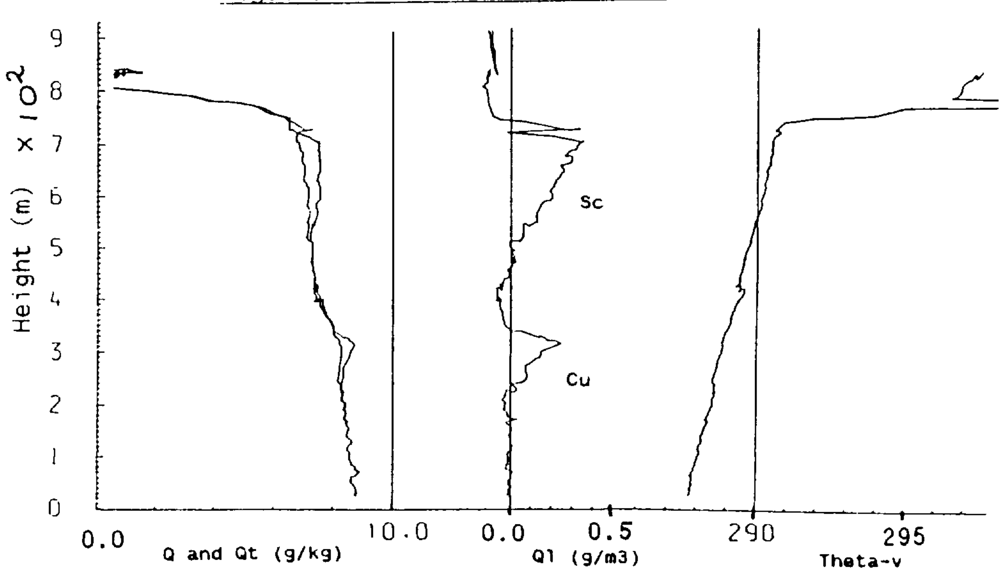
Introduction:

On several occasions during the FIRE Marine Stratocumulus IOP off the Californian coast, small cumulus were observed to form during the morning beneath the main stratocumulus deck. This occurs in the type of situation described by Turton & Nicholls (1987) in which there is insufficient generation of TKE from the cloudtop or the surface to sustain mixing throughout the layer, and a separation of the surface and cloud layers occurs. The build up of humidity in the surface layer allows cumuli to form, and the more energetic of these may penetrate back into the Sc deck, reconnecting the layers. The results presented in this abstract were collected by the UKMO C-130 aircraft flying in a region where these small cumulus had grown to the extent that they had penetrated into the main Sc deck above. In the following paragraphs we will examine the structure of these penetrative cumulus and discuss their implications on the layer flux and radiation budgets.

Aircraft Observations :

An aircraft profile through the boundary layer on the 16th July is shown in fig.1, and illustrates the main features of the case very well. The local time was about midday, and the weak mixing is evident from the slope of the theta-v line. The separation of the layers can be seen as a discontinuity in the Qt profile, although no density interface is visible in theta-v.

Fig.1 : Profiles through boundary layer.



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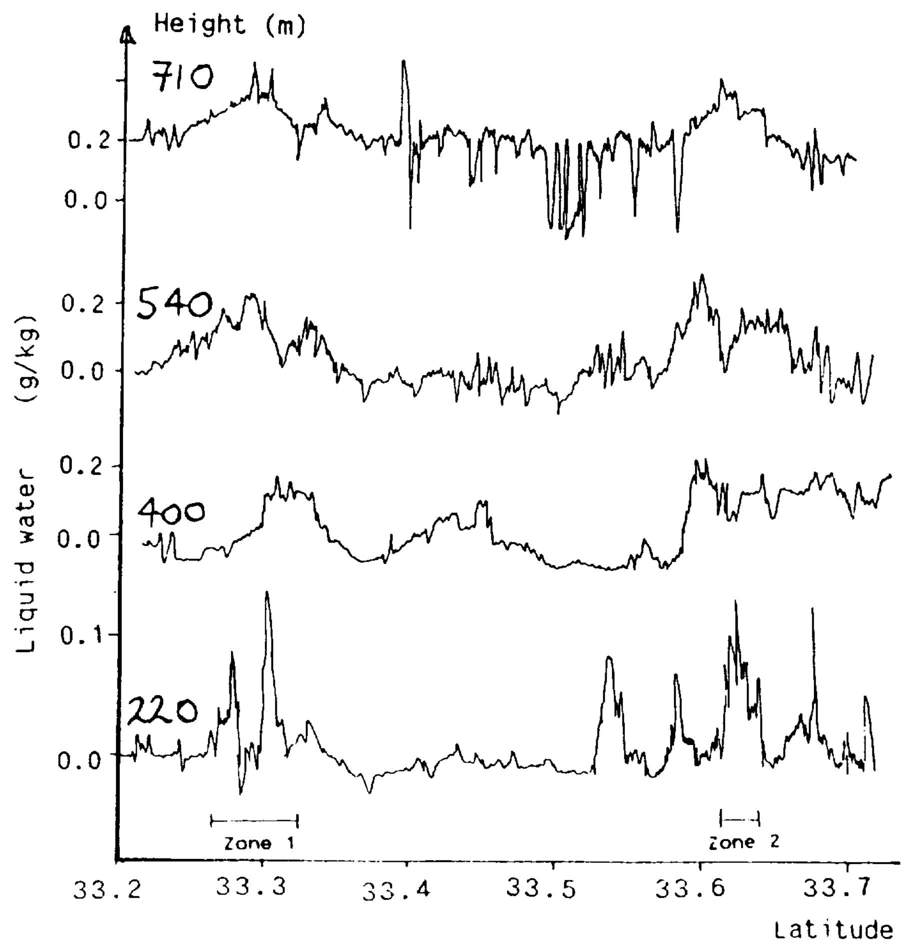
The C-130 flew 60km legs along a north/south line at various levels. Due to the extremely light winds (less than 1.5 m/s mean) the aircraft ground position corresponds to its air position for the section of the flight we will examine. Thus we are justified in overlaying data from different times. Fig.2 represents a cross-section along the flight line for the Johnson-Williams derived liquid water content. Each JW trace has been plotted with its origin position representing the height of the run. The JW values are not absolute. The lower two runs are below the main Sc base, and the upper two are at the Sc base and top. Several areas of small cumulus can be seen in the lower runs, but there are two zones (marked in fig.2) where the enhanced LWCs in the upper runs show that they have penetrated right up to the inversion at the top of the main deck, spreading as they rise. For each run shown the times when the aircraft was well within the cumulus or penetration regions were determined. We can characterise the zones by calculating mean quantities for them separately, and comparing them with the whole-run quantities. (Because the duration flying in the zones is much smaller than the whole run, the whole-run means approximately represent the stratocumulus layer).

Fig.2 : Liquid water cross-section along flight track



Thermodynamics and microphysics:

Taking the surface layer air as representative for the source air of the cumuli, it is found that thermodynamically there is very little difference from the Sc layer air. Mean Theta-e is indistinguishable, but Qt is 8.7 g/kg for the the upper layer and 9.1 g/kg for the surface layer air. These agree with the observed cloud bases from the Ql profiles shown in fig.3(a). The dots are whole-runs and the means from the two zones are numbered accordingly. The best fit line for the zones uses both sets of data. The whole-run profile has a ratio of Ql to the adiabatic value of 0.76, while the zones values is lower at 0.56 due to the ascending Cu entraining air of lower total water content from the surrounding Sc as it rises.

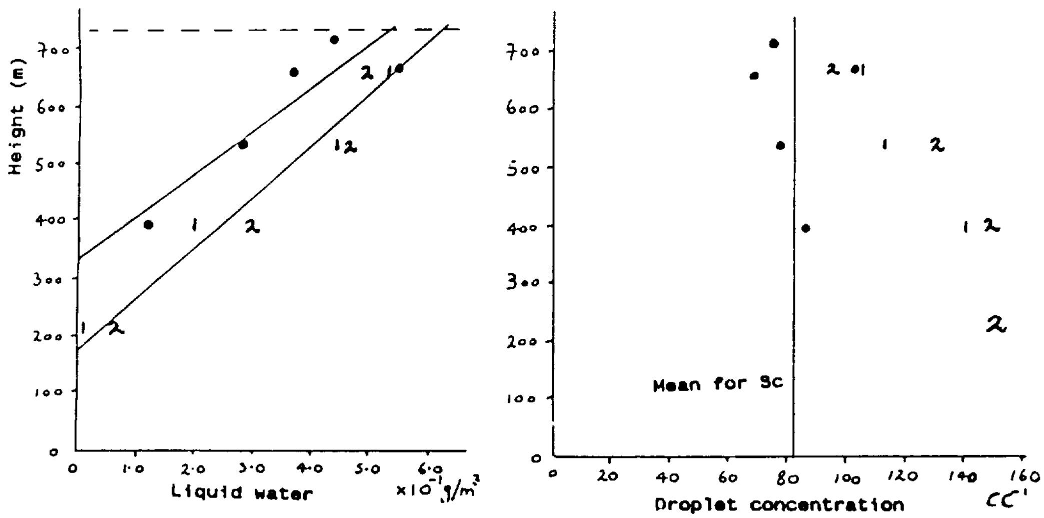


Fig. 3 : (a) Mean Ql profiles. (b) Mean conc. profiles.

This mixing process is well illustrated by the profile of FSSP derived droplet concentrations in fig.3(b). Within stratocumulus droplet concentration is usually found to be constant with height (Nicholls & Leighton, 1986), and so we can use it as a roughly conservative variable. When we look at the microphysics of the zones as opposed to the whole run, we find that the air they are bringing up from the surface layer has a far higher droplet concentration. The whole-run values are constant at about 80 cc-1, whereas the zone values at the Cu cloudbase are close to 150 cc-1. As the Cu plumes rise they spread out and mix with the surrounding Sc layer air, and we see the mean concentration in the zones linearly decreasing until it almost equals the whole-run value by the time the inversion is reached. The profiles of mean volume radius are almost identical for the two situations.

Fluxes:

Both heat and moisture fluxes for the whole-run averages tend to be about half an order of magnitude smaller than typical values from other FIRE flights. Due to their size, the scatter is relatively large and so no pattern can easily be seen. This is consistent with the picture of a poorly mixed layer. It would seem reasonable to expect the fluxes in the zones to be higher, as the Cu carry heat and moisture up through the layer, but here we find a measurement problem. Because of the very short sampling distance in the zones (3 to 4 km) the error variance is large (upto 80% using the method of Lenschow & Stankov, 1986). Thus we cannot determine a representative flux measurement for the zones.

More structure is apparent if we consider the TKE flux (fig.4(a)). The whole-run values are small, but the zone values show a clear maximum at the Cu base, decreasing towards the cloud top (as TKE is used to entrain more quiescent surrounding air) to equal the Sc value. Scatter is still fairly large due to the short sampling period.

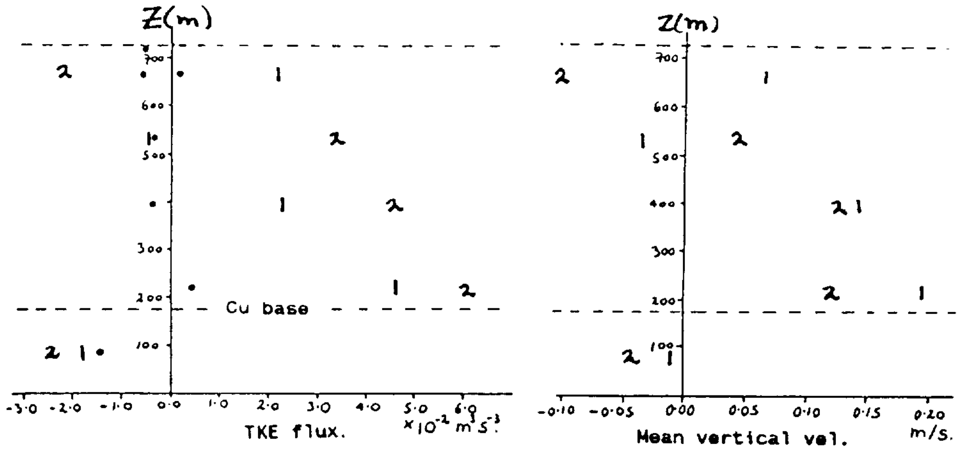


Fig.4 : (a) TKE flux. (b) Mean vertical velocity (in zones)

The mean vertical velocity also shows the structure of the Cu in the zones, following the same trend as the TKE flux. The updraft values are small compared to normal Cu values, but an inspection of a vertical velocity timeseries shows that there are several sharp updrafts within the zones, and that we are averaging across some quiescent areas between them.

Radiation:

Because of the non-linear relationship between cloud water and radiation, it is likely that the radiative properties of the mean cloud will not be the same as the mean radiative properties. So to assess the impact of the presence of the zones on the radiation budget, radiation models using whole-run conditions and zone conditions were compared. The models used were those of Slingo & Schrecker (1982) for the longwave and Roach & Slingo (1976) in the shortwave, with nine levels below the inversion and a subtropical standard atmosphere above it (As Turton & Nicholls, 1987). Comparing the radiative properties of the zones with those derived from whole-run thermodynamics we find that (i) the albedo increases, reflecting more shortwave back into space, and letting less through into the boundary layer and (ii) the absorptance of the cloud increases so that a smaller proportion of the cloudtop flux reaches the ground. The longwave fluxes are virtually unchanged between the two cases. Quantitatively, this means that:

(1) The cloud layer receives 12 Wm-2 more, almost doubling its previous budget of 13 Wm-2.

(2) The surface receives 139 Wm-2 less, a reduction of 37%.

(3) about 130 Wm-2 more are being reflected back into space. This has been verified using the upward and downward facing radiometer data for the two regions. However it is apparent from this data that the regions corresponding to the radiative properties of the Cu are much wider than

the vertical velocities or LWC's would suggest, occupying more than half of the run.

Landsat thematic mapper band-4 reflectivity data taken at the time the C-130 was operating shows bright spots corresponding exactly to the positions of the zones. The Landsat picture shows that regions of penetrative convection lie in streets, and that the C-130 track has cut across about 3 perpendicularly. Hence we know that the cross-section sampled by the C-130 is representative of the whole region. Because band-4 is sensitive to total liquid water column, it also detects small Cu beneath the Sc that have not yet penetrated it, and so there is no sharp change in intensity at the edges of the zones. Thus we cannot use this kind of image *a priori* to diagnose the existence of Cu penetration.

Summary:

Small cumulus were observed to form beneath and penetrate into a stratocumulus sheet. No discontinuity in theta-v could be found between the surface and detached mixed layers, but there was a clear jump of 0.4 g/kg in Qt. FSSP data showed that the surface layer air produced a far higher droplet concentration in the Cu than the Sc layer air above. The decrease of the concentration with height in the Cu shows that the plumes penetrated right up to the inversion, but spread out and entrained lower total water content air as they rose.

Heat and moisture fluxes within the Sc were small, but values could not be determined for the Cu areas due to the short sampling times. In the Cu areas TKE flux and mean vertical velocity both showed a maximum near Cu cloudbase, decreasing as the plumes rose into the Sc.

Using typical values for the Sc layer and the penetrative Cu (regarded as a cloud-layer from Cu base to the inversion) radiative properties were modelled for the two cases. Under the Cu areas the surface budget decreases by 37%, and 130 Wm-2 more are reflected back into space from cloud-top, relative to areas just containing Sc.

Radiometer data showed that the radiation conditions predicted for the Cu occupy more area than suggested by Ql or vertical velocities. Hence any calculation of mean radiative properties based on mean thermodynamic properties will not be valid when penetrative convection is present.

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